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Nutrient Cycling in Willow

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Sweden

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NUTRIENT CYCLING IN WILLOW

by

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PREFACE

In April, 1978, a number of countries within the International Energy Agency (IEA) decided to sign an Implementing Agreement (IA) for a program of research, development and demonstration on forestry energy. The work is implemented via Programme Groups and Cooperative Projects.

Work within the group for biomass growth and production has resulted in many reports which are being published in this series. The funds for the publication of these reports have been supplied by the Biomass Energy Project of the National Research Council of Canada, the Ontario Ministry of Natural Resources and the Canadian Forestry Service.

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ABSTRACT

The objectives of this paper are to summarize the present state of knowledge regarding nutrient cycling in willow (Salix) plantations managed for energy purposes, identify the major gaps, and recommend further research.

Nutrient requirements of intensively-managed willow plantations are high since production may range from 10 to 30 tonnes of stem biomass ha^{-1} yr^{-1} on fertile soils. The associated nitrogen required by plants to sustain such yields amounts to 200 to 600 kg ha^{-1} when plantations are managed on one-year rotations. The production of stem biomass per unit of nitrogen taken up can be almost doubled by extending rotations longer than two years.

Fertilizer requirements are highly dependent on the nutrient status of the soil and the microorganism activity. The need for fertilizers is also influenced by the choice of species, method of culture, frequency of harvest, and degree of plant utilization.

The removal of nitrogen in the harvested stem biomass is from 3 to 8 kg $tonne^{-1}$; the lower value corresponds to harvest cycles longer than two years. Nutrient losses due to leaching will probably be small because of the perennial root system, provided that fertilizer is not applied in large doses.

RÉSUMÉ

La communication a pour objet de faire le point sur l'état actuel des connaissances sur le cycle des éléments nutritifs dans les plantations de saules (Salix) aménagées pour la production d'énergie, d'en déterminer les lacunes et de recommander des recherches pour l'avenir.

Les besoins nutritifs des saulaies aménagées en intensive sont élevés car la biomasse produite des tiges peut y atteindre de 10 à 30 t à l'hectare et par année sur sol fertile. La quantité d'azote nécessaire à une telle production s'élève à 200 à 600 kg/ha, en révolution d'une année. La production de biomasse par unité d'azote assimilée peut presque être doublée par prolongation de la révolution à plus de deux ans.

Les besoins en fertilisants dépendent fortement de l'équilibre nutritif du sol, de l'activité des micro-organismes ainsi que de l'essence, de la méthode de culture, de la fréquence de la récolte et du degré d'utilisation de la plante.

L'exportation d'azote dans les tiges récoltées s'élève à 3 à 8 kg/t; le minimum correspond à des périodes de révolution supérieures à deux ans. L'exportation due au lessivage des sols sera probablement modeste à cause du système racinaire vivace, pourvu que la fertilisation ne se fasse pas à des doses élevées.

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INTRODUCTION

The nutrient cycles in terrestrial ecosystems have attracted the attention of many researchers over the past several decades. The need for a better understanding of these processes in intensive forestry has arisen since the introduction of the energy forestry concept in the mid-1970's. High production in combination with increased tree utilization and shortened rotations could seriously reduce soil fertility, especially if energy plantations are grown on soils with low nutrient availability. Certainly, fertilizer application will play an important role in future short-rotation forestry. However, chemical fertilizers are often not efficiently applied or utilized by plants in both agriculture and forestry; thus, the drain of fertilizer into the ground water could be hazardous to the environment (Konkles, 1973; Nelson, 1977). Consequently, there is an urgent need for the improvement of fertilizer application techniques, and for a better understanding of how fertilizers interact with soil processes, nutrient uptake and primary production, before the introduction of large-scale energy plantations.

Two types of nutrient cycling within a short-rotation willow (Salix) plantation will be considered in this paper: (a) the cycling of nutrients within the tree, the biochemical cycle; and (b) the cycling of nutrients between plants and soil, the biogeochemical cycle. Processes under the influence of the geochemical cycle such as denitrification, volatilization, leaching, mineralization, immobilization, and bulk precipitation in terrestial ecosystems are, in general, thoroughly discussed in the literature, e.g., Clark and Rosswall (1981). Information in this field relevant to energy plantations has recently been published by Fege (1981), Korsmo (1982), Burgess (1982) and Miller (1982 a, b).

Because the interest in growing willows for energy production is very recent, information concerning nutrient cycling in short-rotation willow plantations is scarce. Relevant information exists in literature for other tree genera but has not been considered in this review. There are a large number of references from the early twentieth century dealing with willow production for basketry purposes but these investigations did not consider the nutrient requirements or the nutrient cycling in such cultivation systems. In this paper, available data will be presented together with results gathered from natural willow stands and from experiments carried out in nutrient solutions.

CHARACTERISTICS OF THE GENUS SALIX

The genus Salix consists of about 300 species, most of which are found in the Northern Hemisphere. Willow species normally have relatively short lifespans and except for a dozen species which grow into timber-sized trees, they are shrub-like. This genus is dominant in early succession and usually colonizes land with a good water supply.

As a consequence of considerable genetic variability both within the genus and between individual species, willow cultivars are adapted to a wide range of conditions. Also, they hybridize freely, facilitating the combination of hereditary characteristics.

Most willow species have pre-formed root initials along the stems. Some of the species can withstand flooding and anaerobic root conditions for

long periods. Juvenile growth is rapid and resprouting capacity after coppicing is pronounced. Salix is susceptible to foliar and stem diseases as well as to insects and animal pests that feed on both stems and leaves.

Although willows in general are regarded as species of little economic value, some have been and are still used for different purposes, e.g., erosion and wind control, strengthening of dykes and polders, baskets, bindings, fences, fuel, timber, cricket bats, ornamental uses, and forage for livestock and game.

Willow production in central and eastern Europe is still important, while in western Europe it is on the decline. Currently, there is a considerable global interest in the use of renewable sources of energy, and one such source is plant biomass. Their rapid growth, resprouting capacity, and ease of vegetative propagation are characteristics that make willows suitable for energy plantations. For further information concerning species descriptions, the reader is referred to the work of Fege (1981), FAO (1980), Wasielewsky (1982), Sirén et al. (1979) and Stott (1983).

REVIEW OF THE NUTRITIONAL REQUIREMENTS OF WILLOW

Both the amounts and dynamics of the nutrients cycled in intensively-managed plantations are important in designing means of maintaining productivity of forest sites at an acceptable level in the long term. It is important to identify the nutrient requirements of the species and the amounts of nutrients immobilized, leached, volatilized or removed during harvest. In this context, it is also essential to understand how different management practices interfere with all these processes.

Growth and Yield of Biomass

In order to quantify the nutrient requirments, and thus the possible need for fertilizers, in an intensively-managed willow plantation, the production level of stems, leaves and roots must be known for the specific growing environment.

Stem Production

Initially, growth of willows is very rapid under greenhouse conditions. Plants may double their weight in less than one week, provided sufficient nutrients and water are supplied (Ericsson, 1981 a).

Data from the literature dealing with annual stem production in willow plantations range from 6 to almost 35 tonnes d.w. ha^{-1} (Table 1). The large variation in yield must result from differences in climate, edaphic conditions, genetics and cultural practices.

From production models, based on both laboratory and field experiments, the maximum stem biomass production for willow plantations in southern Sweden would approach 20 tonnes ha^{-1} yr^{-1} (Linder and Lohammar, 1982). Such yields from intensively managed plots in southern Sweden have recently been reported (Sirén, 1980). A more prolonged growing season than that in Sweden will increase yields by another third, as indicated by the very high production levels reported in Italy (May, 1982) and New Zealand (Hathaway and van Kraayenoord, 1981; Hawley, 1981).

The importance of the duration of the growing period is further demonstrated in Figure 1, which shows that the maximum rate of dry matter accumulation of stems in willow stands located in southern Sweden occurs late in the summer.

Table 1: Annual Stem Production in Willow Plantations

Stem yield tonnes/ha/year	References	
0 - 10	McCarthy	1979
	Ceyer	1981
	Kestemont	1974
10 - 20	Bialkiewcz & Nowinski	1968
	Janin & Durand	1975
	Krstinic & Vidakovic	1964
	McElroy & Abernethy	1976
	Pohjonen	1980
	Sirén	1980
20 - 30	Hathaway & van Kraayenoord	1981
	May	1982
30 - +	Hawley	1981

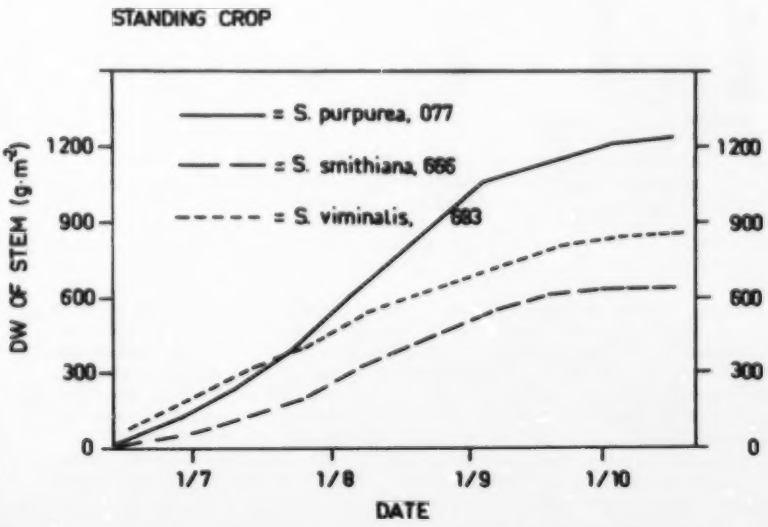

Figure 1. Calculated standing crop (DW) of different willow clones per unit of area for stems during the 1980 growing season (after Nilsson, 1982).

Factors that affect photosynthesis and respiration play key roles in the search for ways of improving productivity. The nutrient status of the plant is a factor over which we may exert considerable control and our interest is justified because photosynthesis (McDonald et al., 1981) and growth (Ericsson, 1981 a, b) are linearly correlated with the nitrogen (N) status in several species of willow.

The qualitative nutrient requirement of Salix aquatica, S. purpurea and S. viminalis (Ericsson, 1981 a, b) at optimal growth under laboratory conditions are very similar to those of birch (Betula verrucosa) and grey alder (Alnus incana) (Ingestad, 1981). The relative weight proportions (N = 100) between the macroelements required at optimum growth for these willow species compared with birch and grey alder are given in Figure 2.

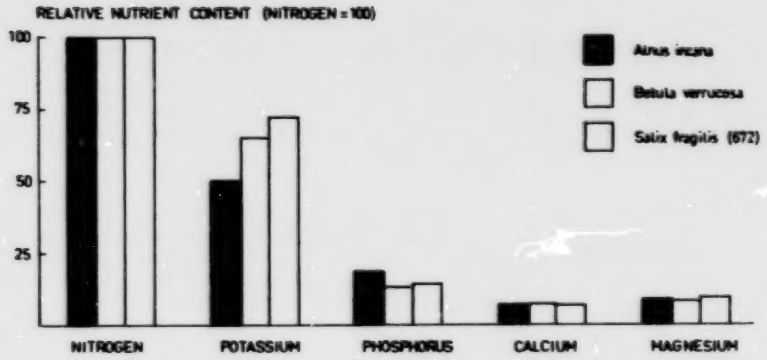

Figure 2. Nutrient weight proportions (N = 100) required for maximum growth rate of young Salix fragilis, Betula verrucosa and Alnus incana (after Ericsson, 1981 b; Ingestad, 1981).

The nitrogen status of plants exerts a strong influence, not only on the process of photosynthesis but also on the dry matter allocation between the different plant parts. A properly fertilized willow plant grown in nutrient solution expends less of its photosynthetic products on root growth than do nutrient-deficient plants (Figure 3). The same trend of dry matter distribution in relation to nitrogen status has also been found under field conditions in a Pinus silvestris stand located in central Sweden (Linder and Axelsson, 1982). The relative allocation to below-ground production in the carefully fertilized and irrigated stand was approximately half that of the control.

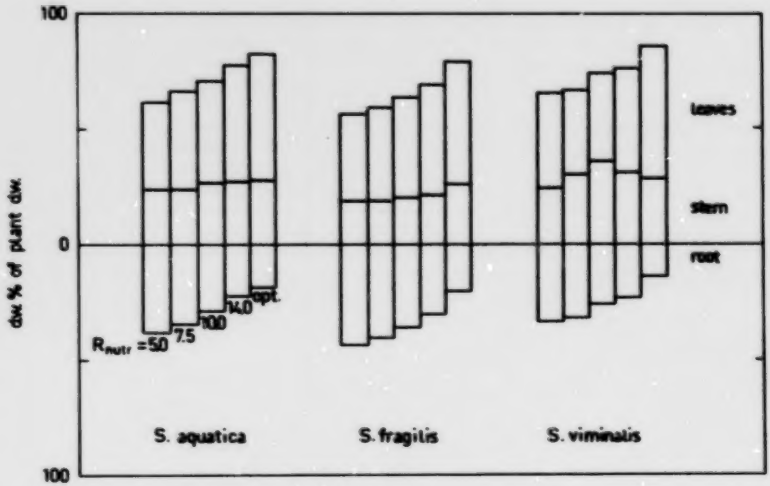

Figure 3. The distribution of dry matter between roots, stems and leaves expressed as percent of total plant dry weight at different rates of nutrient addition (after Ericsson, 1981 b).

An optimally fertilized plant not only produces less roots but also less total biomass per unit of nitrogen absorbed (nitrogen efficiency), compared with a plant grown under limited nitrogen conditions (Figure 4).

The rate of biomass production per unit of nitrogen taken up (nitrogen productivity), therefore, is positively correlated to the nitrogen status of the plant (Figure 5).

Conclusion

Production levels in the range of 10 to 30 tonnes ha^{-1}, depending on climate, seem realistic in future large-scale plantations if they are established on fertile soils or if nutrients and water are supplied in sufficient amounts on limiting sites.

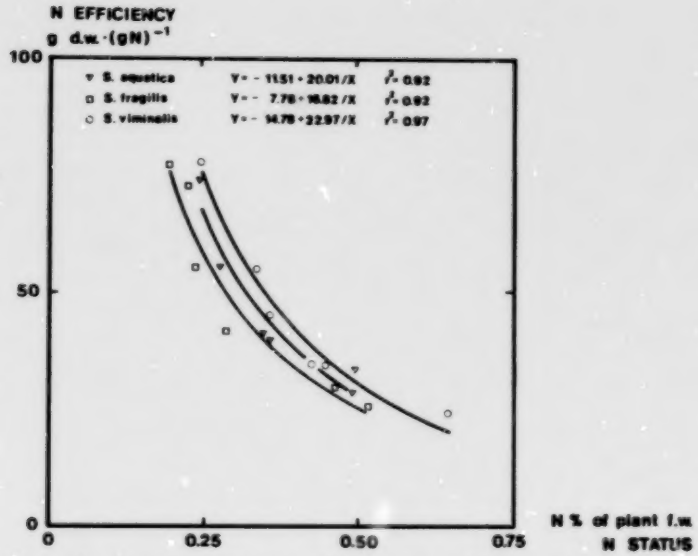

Figure 4. Nitrogen efficiency (dry matter production per unit of nitrogen taken up) of three Salix clones at different levels of nitrogen status (after Ericsson, 1981 a).

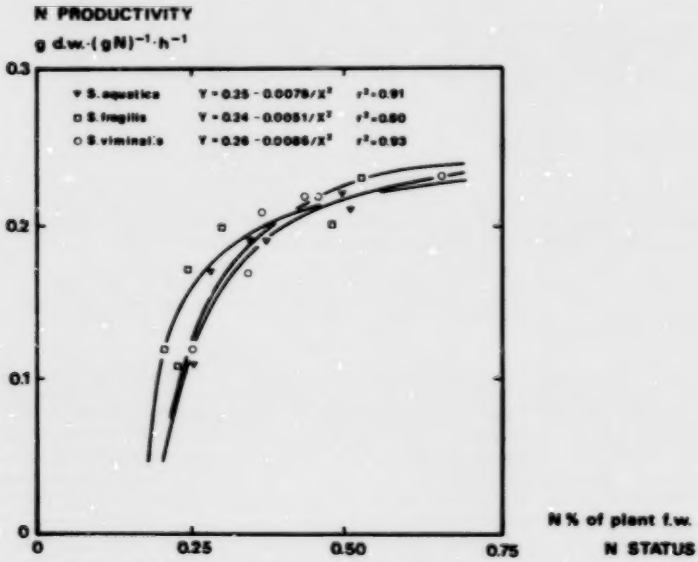

Figure 5. Nitrogen productivity (dry matter production per unit of time and unit of nitrogen taken up) of three Salix clones at different levels of nitrogen status (after Ericsson, 1981 a).

Leaf Production

Leaves play the key role in the growth processes of plants and contain more nutrients per unit weight than stems and roots. However, little is known about the production of leaves in willow plantations.

Knowledge concerning leaf growth in relation to species/clone, stem growth, season, spacing, stand age, rotation length, and rotation number is essential in order to estimate the nutrient requirements in various types of willow plantations.

One attempt to describe the seasonal growth of leaves of different willow clones has been made by Nilsson (1982). Maximum leaf weight of one-year-old shoots of three species was measured during early September (Figure 6). The total leaf production at that date was 8% to 15% higher than shown in Figure 6 because some leaves had already fallen (Nilsson, pers. comm.). The ratios between dry weight of final stem production and maximum dry weights of leaves in this example were 2.5 for clone 077 (S. purpurea), 3.0 for clone 683 (S. viminalis) and 2.0 for clone 666 (S. smithiana). This indicates species differences in carbon allocation.

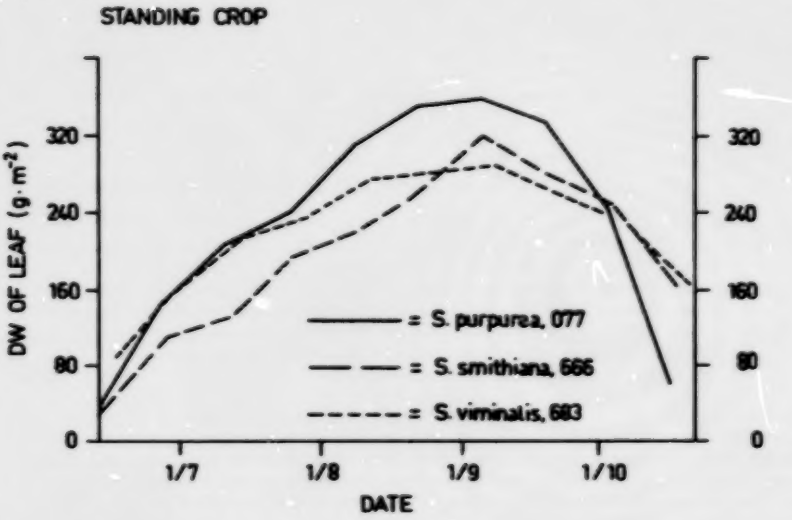

Figure 6. Calculated foliar dry matter weight (DW) of different Salix clones per unit area during the 1980 growing season (after Nilsson, 1982).

A total leaf production of almost 7 tonnes dry weight (d.w.) per hectare has been measured on current shoots in a S. viminalis (clone 082) stand (three-year-old roots) yielding 15 tonnes of dry stems (Nilsson, pers. comm.). The production of leaves tends to increase with increased shoot age. In a S. viminalis stand (clone 683), 16 plants/m^2) with two-year-old stems, 6.3 tonnes d.w. of leaves were produced per hectare; 3.5 tonnes of leaves were produced in a similar one-year-old plantation (Figure 7).

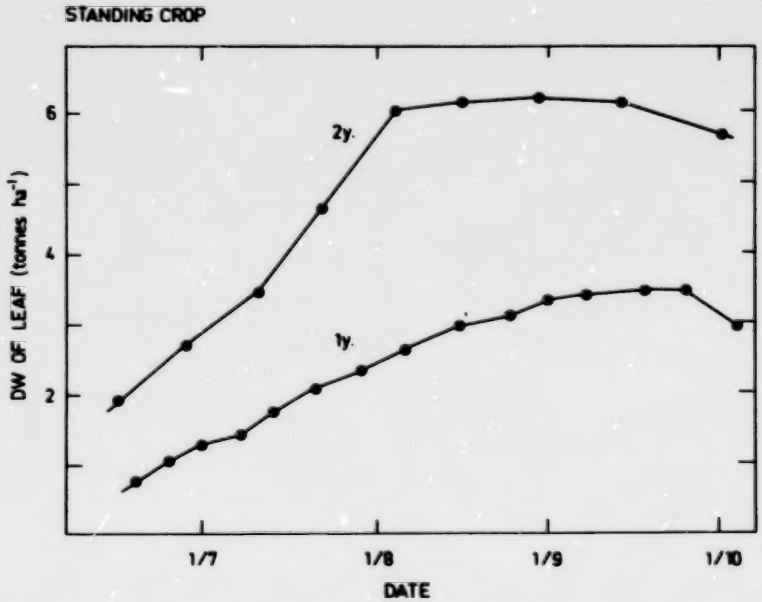

Figure 7. Calculated dry matter weight (DW) of leaves from one- and two-year-old shoots of Salix viminalis (clone 683) during the 1981 growing season (after Nilsson, 1983).
Note: this figure shows leaves attached to the trees and not the accumulated leaf production.

Even higher leaf weights have been reported from New Zealand. On one occasion, 6 to 10 tonnes of dry matter per hectare of willow leaves and small twigs were harvested following three and a half months growth from stumps (Hawley, 1981).

Besides the influence of species characteristics and shoot age upon leaf production, the nutrient status of the crop strongly affects the yield of leaves; improved nutrition considerably increases leaf production in relation to stems and roots (Figure 3).

Conclusion

An annual leaf production of 3.5 to 10 tonnes d.w. ha^{-1}, depending on species, shoot age, soil fertility and climate, may be expected in high-yielding (10 to 20 tonnes ha^{-1}) willow plantations.

Root Production

Information concerning root production under field conditions in established willow plantations is scarce. The rooting pattern of S. triandra var. Black Maul, planted on a clay soil at Long Ashton Research Station in southern England, was studied during a seven-year period (Stott, 1961). The cuttings were planted at a 0.92 x 0.92 m spacing and root growth and distribution were followed annually (Table 2). The root systems showed significant increases in weight up to the sixth year. At that time a root biomass corresponding to 3.47 tonnes d.w. ha^{-1} was recorded but, unfortunately, the ratio of root-to-shoot biomass cannot be determined from this investigation since no data on stem and leaf growth are given.

In young willow plants grown in nutrient solution, 15% to 30% of the dry matter production, depending on the nutrient status of the plant, consisted of roots (Ericsson, 1981 a, b). From experiments carried out on a raised peat bog in central Sweden, 10% to 30% of the standing biomass of S. aquatica consisted of roots in late September of the year it was planted (Elowsson, pers. comm.). In a coppiced natural willow stand that was fourteen years of age, roots were equivalent to 21% of the aerial biomass (Kestemont, 1974). Unfortunately, no investigation dealing with the production and rapid turnover of the fine root fraction has so far been conducted on willows, and neither have studies been made of root growth in relation to species, spacing, rotation length, or the number of rotations.

In the growth model presented by Linder and Lohammar (1982), 25% of the total annual biomass production in an optimally fertilized willow plantation consisted of roots. If this assumption is correct, a root production of 10 tonnes ha^{-1} is to be expected in a willow plantation producing 20 tonnes of stems and 10 tonnes of leaves d.w. ha^{-1} $year^{-1}$.

The production of roots, as shown in Figure 3, is strongly influenced by the nutrient availability in the soil. The functioning of willow roots, i.e., nutrient uptake and growth, is also dependent on the soil pH. A pH lower than 4.0 almost totally restricts root growth of e.g., S. viminalis, whereas the same pH level has no influence upon the growth of birch and grey alder (Ericsson and Lindsjö, 1981).

Conclusion

The standing biomass in a willow plantation consists of 10% to 30% roots. A root fraction equivalent to 25% of the total biomass production (roots, stems and leaves) has been suggested when willows are grown under favourable nutrient conditions. When growing willows under less favourable nutrient conditions, a larger fraction of the total biomass production will be expended on root growth (Linder and Axelsson, 1982).

Table 2: Growth and Distribution of Roots on Willow Cuttings (after Stott, 1961)*

	1954	1955	1956	1957	1958	1959	1960
No. of root system sampled	24	48	48	48	16	8	8
Length of rooted cutting (in.)	11.4	11.8**	11.1**	10.8	10.6	10.2	10.3
Diameter of cutting (in.) at base	11.4	11.0	11.5	12.3	12.0	17.1	18.8
Diameter of cutting (in.) at ground level	14.4	15.9	22.6***	38.0***	50.6***	60.3***	57.5
Length of longest root (in.)		22.9	44.3***	66.6***	85.1**	96.8	85.6
Depth of point of origin of longest root (in.)		6.9	6.2	6.0	6.0	5.9	5.5
Dry weight of root system (g)	6.8	8.9	37.9***	119.9***	275.6***	415.1**	318.9
Dry weight (%) in zones 0 - 3		12.0	19.2	24.8	30.9	18.3	27.9
		***	***	*		*	
3 - 6		38.7	35.2	33.6	29.4	43.3	31.1
0 - 6	60.4	50.7	54.4	58.4	60.3	61.6	59.0
	*			*			
> 6	39.6	49.3	45.6	41.6	39.7	38.4	41.0
No. of roots originating from the cutting	49.9	51.7	54.3	48.2*	41.1*	31.6*	25.8
No. (%) in zones 0 - 3		18.5	19.9	26.3**	38.7***	37.7	36 7
3 - 6		20.0	25.1	25.1	22.1	31.2	24 8
0 - 6	41.4	38.5	45.0**	51.4**	60.9***	68.9	61 5
> 6	58.6	61.5	55.0**	48.6**	39.2***	31.1	38 5

* Figures significantly different from those of the previous year (or a different rooting zone) at the 5%; ** at the 1%; *** at the 0.1% level.

Nutrient Content in Biomass

Nutrient Content of Stems

The highest mineral content of willow stems is found in young, vigorously growing shoots less than 30 cm in height (Table 3). A nitrogen concentration of 2.5% (d.w.) is not unusual when plants are grown in the laboratory under optimal nutrient conditions.

Table 3: Mineral content (% of d.w.) in stems of young Salix viminalis plants (15 to 30 cm in length). (Data from Ericsson, 1981 a, b; Ericsson, unpubl.).

Element	N	K	P	Ca	Mg
	% of d.w.				
Stem	2.47	2.37	0.25	0.57	0.22

The experiments were carried out under controlled climatic conditions and nutrients were given in excess.

From the beginning of the growing period until the first days of July, willow plants absorb almost all the nitrogen, phosphorus and potassium which is to be found in the crop (Jezewski, 1960). However, the sequence of nitrogen uptake in four S. viminalis stands located in southern Sweden showed that the quantitative nitrogen uptake is closely linked to the biomass production (Nilsson and Ericsson, in prep.). Only about 40% of the final nitrogen uptake was present in the shoots at the beginning of July (Figure 8).

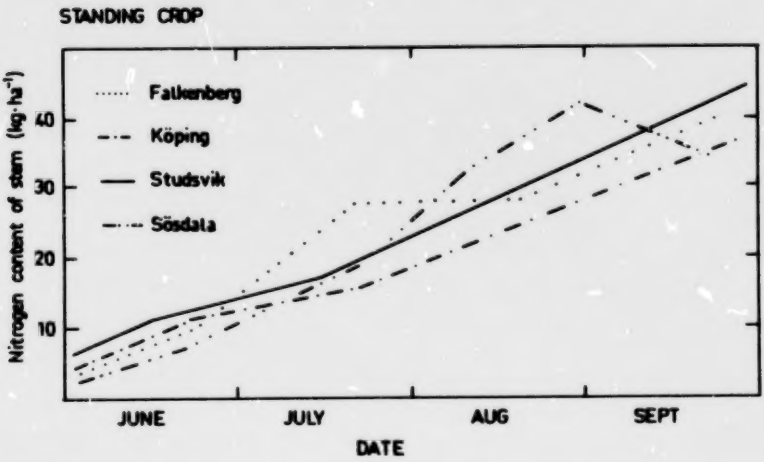

Figure 8. Calculated nitrogen content (kg) in stems of Salix viminalis per hectare at four localities in Sweden during the 1981 growing season (after Nilsson and Ericsson, in prep.).

The seasonal changes in nutrient element concentrations of tall shrubs, including willows, have been studied by Grigal et al. (1976). After an early season decline, nitrogen concentration in current twigs and stems increased during and slightly after leaf fall (Figure 9). Similar trends were observed in the four intensively-managed S. viminalis stands located in southern Sweden (Figure 10.).

After leaf fall in the first growing season, stem nitrogen concentrations are commonly in the range of 0.5% to 0.8% (d.w.) in willow plantations (Table 4). Some clones seem to accumulate more nitrogen than others when grown under comparable conditions (cf. S. smithiana, S. viminalis and S. purpurea). However, external factors such as the soil nitrogen level exert a stronger influence upon the tissue nitrogen concentration as compared with genetically mediated factors. High levels of nitrogen in the soil or a disturbed balance between nitrogen and the other nutrient elements might give rise to a luxury consumption of this element. The very high nitrogen contents, 1.11% to 2.45% (d.w.) in stems of S. purpurea and S. viminalis reported by Kawecka (1976), are most likely a result of this. These plants were grown in soil exposed to severe nitrogen pollution.

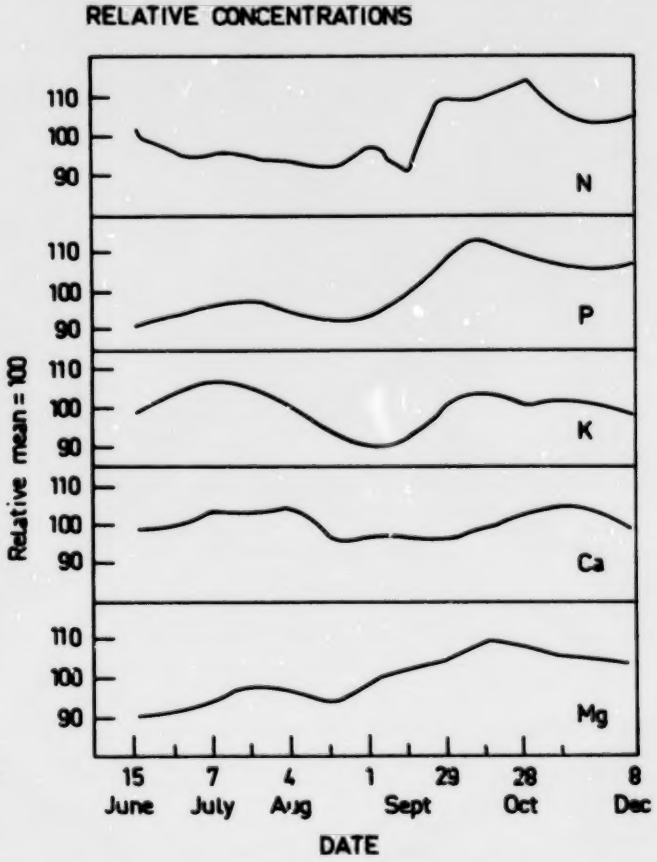

Figure 9. Seasonal fluctuations in stem composition of tall shrubs from northeastern Minnesota. The curves are based on data gathered from five species, including Salix spp. The mean stem concentration of all species is set at 100 (after Grigal et al., 1976).

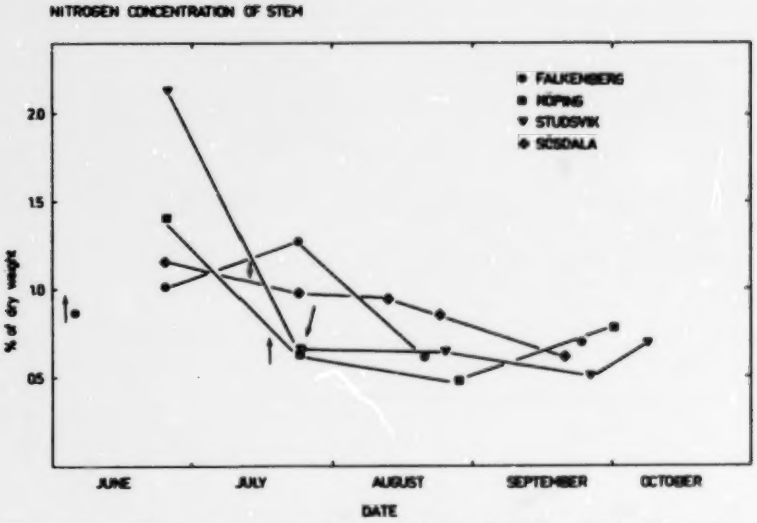

Figure 10. Nitrogen concentration in stems of Salix viminalis at four localities in Sweden during the 1981 growing season. Application of fertilization (100 kg N ha^{-1}) is indicated by arrows (after Nilsson and Ericsson, in prep.).

Table 4: Mineral Content (% of d.w.) in Willow Stems (bark + wood).

Species	N	K	P	Ca	Mg	References
S. smithiana (clone 666)	0.75	0.38	0.12	0.48	0.06	Ericsson, unpubl.
1-year-old shoots						
S. viminalis (clone 082)	0.49	0.35	0.09	0.33	0.05	- " -
S. purpurea (clone 077)	0.57	0.18	0.09	0.33	0.05	- " -
1-year-old shoots						
S. spp.	0.39	0.14	0.06	0.58	0.05	Grigal et al., 1976
Osier shoots	0.5-0.6	0.16-0.18	0.05	0.47-0.78	-	Jezewski, 1960
S. viminalis	1.12-2.45	-	-	-	-	
S. purpurea	1.11-1.54	-	-	-	-	Kawecka, 1976

The macroelement concentrations in wood and bark at the end of the first growing season are generally higher in the upper parts of the shoot (Table 5.)

Table 5: Mineral Content (% of d.w.) in Wood and Bark at Different Positions on One-year-old Shoots (2.0 to 2.5 m) of *Salix smithiana* (data from Ericsson, unpubl.).

		N	K	P	Ca	Mg
Top	Bark	1.44	0.75	0.19	0.74	0.08
	Wood	0.80	0.38	0.12	0.36	0.05
Middle	Bark	1.00	0.52	0.14	0.72	0.07
	Wood	0.41	0.20	0.09	0.18	0.04
Base	Bark	1.43	0.83	0.18	0.14	0.11
	Wood	0.52	0.22	0.10	0.31	0.05

From available data it may be estimated that a 10 tonnes ha^{-1} yield of one-year-old willow stems contain 55-65 kg nitrogen, 22-26 kg phosphorus (P), 28-48 kg potassium (K) and 30-119 kg calcium (Ca) (Table 6).

Table 6: Mineral Content (kg ha^{-1}) in a Crop Containing 10 Tonnes of One-year-old Willow Shoots

Contents of (kg ha^{-1})				References
N	P	K	C	
58.8	22.4	28.0	29.9	Hutchinson, 1924
54.7-66.7	23.8-26.2	42.8-47.6	71.4-119.0	Jezewski, 1960
93.0-144.0				Kawecka, 1976
125.0				Pohjonen, 1980
65.0				Nilsson & Ericsson, in prep.

The very high nitrogen contents reported by Pohjonen (1980) and Kawecka (1976) can, at least in the latter case, be explained by unusually high soil nitrogen levels.

The nitrogen concentration of willow stems decreases with age but levels out after shoots reach an age of three years in dense plantations (0.5 m x 0.5 m). By this age, the nitrogen concentration has decreased to about 0.4%. A somewhat lower stem nitrogen content is to be expected if tree-type willows are grown for long rotations (ten to twenty years), because of the increased wood-to-bark ratio.

Conclusions

The removal of nutrients from the forest floor, when taking an annual harvest of 10 tonnes ha^{-1} from willow plantations, will be in the order of 55-65 kg N, 22-26 kg P, 28-48 kg K and 30-119 kg Ca. By choosing rotations of two years or more, the removal of nitrogen per tonne can be reduced by almost 50%.

Nutrient Content of Leaves

The foliage of a plant represents a major site of nutrient turnover. Although nutrients are lost during leaf fall, many of the mobile nutrients can be reabsorbed from the foliage before leaf abscission. Species grown under severe nutrient limitations, like bog plants, reabsorb more nutrients from their foliage preceding leaf fall than upland species (Small, 1972).

The nitrogen content of leaf litter seems to be positively correlated with the capacity of the soil to supply nutrients (Berg and Staaf, 1980). However, retranslocation of nutrients from leaves back into stems can also be an important process at sites with high nutrient availability (Ryan, 1978).

Grigal et al. (1976) found that the concentration of nitrogen, phosphorus and potassium in leaves of willow from a natural stand dropped, while calcium and magnesium increased, prior to leaf abcission (Figure 11). When seasonal changes in foliage weight are taken into consideration, the mass of calcium and magnesium (mg $leaf^{-1}$) showed an increase from June to September and decreased thereafter. This indicates that these elements are also retranslocated to the woody parts or are leached prior to leaf fall. Similar trends, except for calcium in the mineral concentration of S. nigra leaves from a natural flood plain community, have been reported by Garten et al. (1977).

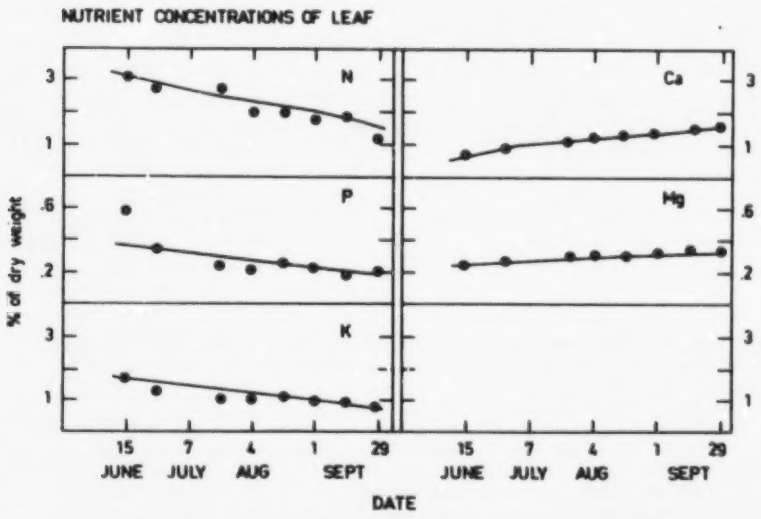

Figure 11. Concentration of five nutrient elements with time in leaves of Salix spp. from northeasern Minnesota (after Grigal et al., 1976).

The nitrogen concentration with time and the course of nitrogen uptake in leaves throughout the growing season in current shoots of S. viminalis (clone 082) collected from four localities in southern Sweden, is shown in Figures 12 and 13. The nitrogen uptake in the above-ground biomass varied from 100 to 205 kg ha^{-1}, 60% to 71% of which was found in the leaves. This data was obtained from stands producing 6.8 to 9.8 tonnes of steus (d.w.) and 2 to 4 tonnes of leaves (d.w.) ha^{-1} yr^{-1}. The effect of nutrient application on the leaf nitrogen content is also demonstrated in Figure 12. The bad timing of the fertilizer application in relation to demand, as in the case of Köping, Studsvik and Sösdala, probably resulted in growing losses.

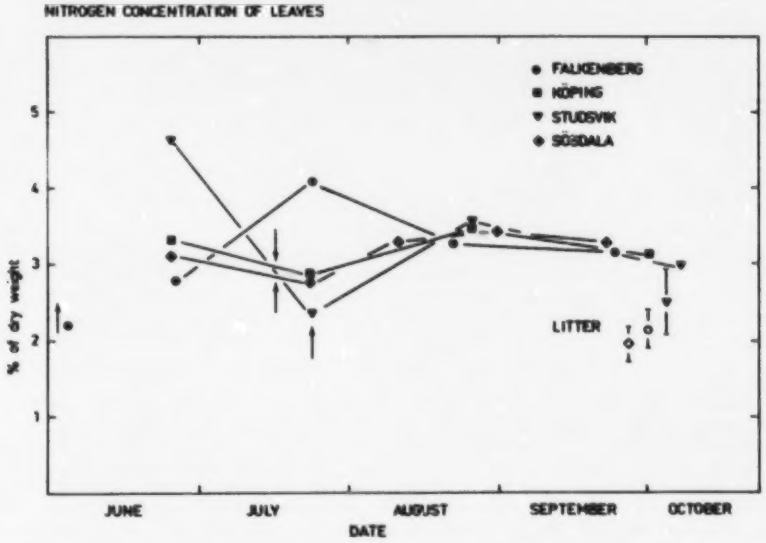

Figure 12. Nitrogen concentration in leaves of Salix viminalis at four localities in Sweden during the 1981 growing season. Application of fertilization (100 kg N ha^{-1}) is indicated by arrows (after Nilsson and Ericsson, in prep.).

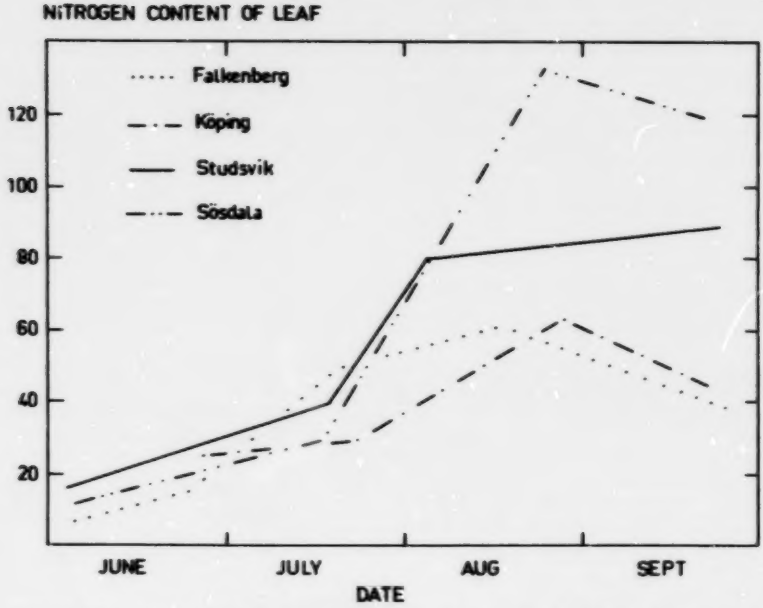

Figure 13. Calculated nitrogen content in leaves of Salix viminalis at four localities in Sweden during the 1981 growing season. The nitrogen content in leaf litter is not included (after Nilsson and Ericsson, in prep.).

After leaf fall, 70% of the leaf nitrogen reported in Figure 13 was transferred to the leaf litter. The rest was retranslocated back into the twigs and stems or lost through leaching.

The nutrients withdrawn are largely transported to storage locations in the stems (Sauter, 1981). This nutrient pool makes the plant nutrition independent of the soil nutrient pool during the critical period of early spring growth.

Estimates from a mid-successional birch-beech-maple forest show that 33% of the annual nitrogen required to sustain plant growth processes came from the mobile pool of nitrogen within the tree (Ryan, 1978). A rough calculation based on the data presented (Figures 12 and 13) indicates that 20% to 25% of the nitrogen required for shoot growth in the second year (unchanged production level) can be derived from this pool in a willow plantation. Consequently, the mobile nitrogen pool is most important for the nitrogen economy of short-rotation forests being managed on rotations longer than one year.

Conclusions

A seasonal uptake of nitrogen reaching 100 to 300 kg ha^{-1} in leaves, depending upon species, shoot age, soil fertility and climate, may be expected in high-yielding (10 to 20 tonnes ha^{-1} yr^{-1}) willow plantations. Approximately one-third of the nitrogen is reabsorbed from the foliage prior to leaf abscission. The corresponding uptake of P, K, Ca and Mg would be 7-20 kg, 35-100 kg, 60-170 kg and 12-35 kg respectively. However, these figures might be somewhat underestimated since the leaf concentration data used here was derived from a natural willow population (Grigal et al., 1976).

Nutrient Content of Roots

No data on the nutrient contents of roots, fine or coarse, are available from field-grown willows. However, from experiments carried out under laboratory conditions with nutrient solutions, concentrations in fine roots were similar to those of young stems, except for nitrogen and potassium which were comparable to the levels reported for leaves (Table 7, Ericsson unpubl.).

Table 7: Mineral Content (% of d.w.) in Roots of Young Salix viminalis Plants (length, 15 to 30 cm).

Element	N	K	P	Ca	Mg
		% of d.w.			
Root	3.18	4.05	0.30	0.36	0.24

If willow roots were to behave similarly to those of pine, more than 200 kg ha^{-1} of nitrogen would be found in the root biomass of a willow plantation producing 10 tonnes of roots ha^{-1} $year^{-1}$, assuming a nitrogen concentration in fine and coarse roots of 3% and 0.6%, respectively, and a fine-to-coarse root ratio of 1.5. However, the nitrogen content within the root biomass at any given time will be considerably lower because of the rapid turnover of fine roots. Thus, a large fraction of the annual nitrogen requirement for root growth may be met from the rapidly decomposing fine-root litter.

Conclusion

The distribution of dry matter (tonnes ha^{-1}) and the corresponding nitrogen content (kg ha^{-1}) in roots, stems and leaves in willow plantations producing 10 and 20 tonnes ha^{-1} yr^{-1} stem biomass are summarized in Table 8. It must, however, be emphasized that these calculations are estimates, especially with regard to roots, and based on data obtained from growth modelling (Linder and Lohammar, 1982) and laboratory investigations (Ericsson 1981 a, b).

Confirmation of this data is of the utmost importance in order to fully understand the growth dynamics and nutrient requirements of managed willow plantations.

Table 8: Estimated Partitioning of Dry Matter (tonnes ha^{-1}) Between Roots, Stems and Leaves and the Corresponding Nitrogen Contents (kg ha^{-1}) in Willow Plantations Producing 10 and 20 Tonnes of Dry Stem Biomass ha^{-1} yr^{-1} Respectively.

Organ	Dry matter production		Nitrogen content kg ha^{-1}	
	tonnes ha-1 yr-1		10t stem	20t stem
root	5	10	110	220
stem	10	20	60	120
leaf	4	10	120	300
total	19	40	290	640

LITTER PRODUCTION AND MINERALIZATION

Relatively little of the nitrogen utilized annually within undisturbed ecosystems comes from biological fixation or atmospheric inputs; most is derived from the soil-plant-microbe system (Melillo, 1981). In this sequence of recycling processes, most of the nitrogen transferred from the vegetation to the soil is in the organic form. Since almost all of the nitrogen taken up by plants is in the inorganic form, mineralization, or the transformation of organic nitrogen to inorganic nitrogen, is the key process in the nitrogen cycle.

The rate of the transformation process and the fate of the mineralized nutrients depend upon a number of biotic, as well as abiotic, factors. Soil pH, temperature, and water content, as well as litter nitrogen and lignin concentrations, all affect the soil microbial composition and activity.

Litter fall is the dominant above-ground transfer pathway of nutrients to the soil. Leaf litter normally, and especially in short-rotation forests, accounts for the largest amount of nutrients in the litter fall. However, several studies in mid-successional deciduous forests have suggested that root litter, particularly fine-root litter, is quantitatively the most important pathway of nitrogen transfer between plants and soil (Harris et al., 1973; McGinty, 1976). Unfortunately, the production of fine-root litter in intensively-managed willow plantations has not been quantified, nor has the release of nutrients from this litter source been studied.

Willow leaves are generally considered to be easily decomposed. Leaves from a natural willow stand in Michigan lost 37% of their initial nitrogen contents during the first year of decomposition (Chamie and Richardsson, 1978). The 50%, 95% and 99% turnover time for nitrogen was 1.51, 6.54 and 10.89 years, respectively.

Corresponding data relevant to intensively-managed willows plantations is not available from the literature. However, pilot studies carried out within the Swedish Energy Forestry Project indicate that great differences in litter quality exist among the willow species (Granhall,

Slapokas, pers. comm.). The leaf litter differed with respect to nitrogen and lignin contents, the amount of water-soluble nitrogen compounds, as well as the rate of decomposition. Leaves of S. viminalis (clone 082), having an initial nitrogen content of 2.7%, lost 20% of their organic nitrogen during the first year of decomposition whereas S. purpurea x viminalis (077) leaves, at a 1.7% initial nitrogen level, showed no net mineralization even after three years of incubation (Granhall, 1982).

The nitrogen concentration of leaf litter is dependent on both soil nitrogen conditions (Berg and Staaf, 1980) and choice of species (Granhall, Slapokas, pers. comm.). Species imported from southern latitudes grow and keep their foliage green far longer in the autumn than those native to Swedish sites. The mobile nutrients in the leaves of such species are not efficiently reabsorbed and the leaves are often dropped green. This type of leaf litter increases the amount of nitrogen available for plant uptake in the following year. The losses of nitrogen in the harvested stem biomass will be correspondingly reduced because less of the mobile leaf nutrients will be stored in the woody parts after leaf abscission.

Conclusion

Available data indicates that a contribution in the order of 20 kg N ha^{-1} from leaf litter to the nitrogen economy of a willow stand can be achieved as early as the second year. The release of nitrogen and other nutrients from leaf litter during subsequent years will increase in parallel with the increased litter production and accumulation on the forest floor. Whether the amount of nutrients made available for plant uptake by the mineralization process can sustain plant growth processes at an acceptable level, or whether regular applications of fertilizers are required in established willow stands, remains to be tested. It must be noted in this context that part of the mineralized nutrients will be consumed by the microorganisms themselves. This would create a substantial demand for fertilizers, at least during the stand establishment phase and particularly if plantations are grown on lands with an initial low nutrient status.

FACTORS AFFECTING YIELD AND NUTRIENT REMOVAL IN WILLOW PLANTATIONS

A critical question for forest management is whether the soil has the capacity to maintain a supply of nutrients sufficient to sustain productivity at an acceptable level over the long term (Crane and Raison, 1981). This question is particularly critical in short-rotation forestry.

The rate at which nutrients are removed from the forest site can be considerably influenced by management practices and is dependent on the choice of species/clone, level of production, density of planting, length of rotation and degree of harvesting.

Differences in mineral content exist among woody debris for some tree species. For example, logs of Pinus radiata older than seven years contain three to five times more phosphorus than Eucalyptus delegantensis of comparable age (Crane and Raison, 1981).

At present, there is no data showing significant species or clonal differences with respect to the mineral concentration of wood and bark in the genus Salix. However, the percentage of bark in current shoots

varies significantly (Table 9), and the mineral content of bark is higher than in wood (Tables 6 and 10).

Table 9: Mean Bark Percentage (BP) Per Clone, Standard Deviation (SD) and Ranking Order During 1979-81 (after Sennerby-Forsse et al., 1983).

Species/Clone		1979			1980			1981		
		BP %	SD	Rank order	BP %	SD	Rank order	BP %	SD	Rank order
S. viminalis	175	31.5	0.2	11	28.7	1.8	3	37.9	4.7	1
S. fragilis	094	39.0	2.6	2	34.2	1.5	1	37.8	2.8	2
S. viminalis	054	34.7	0.2	4	27.2	1.7	6	34.0	2.4	3
- " -	195	32.7	0.4	7	28.6	3.1	4	31.2	2.1	4
- " -	091	28.3	0.3	15	23.8	0.4	15	30.0	2.9	5
- " -	090	28.1	0.6	16	28.5	2.6	5	29.7	2.3	6
- " -	003	30.3	0.5	14	25.4	1.7	10	29.4	3.0	7
- " -	120	30.8	0.4	13	23.4	0.5	17	27.8	1.4	8
- " -	112	33.9	0.5	6	26.4	1.5	9	27.5	1.4	9
S. aquatica	133	27.3	0.5	17	24.3	1.8	12	27.4	1.7	10
- " -	104	23.0	0.5	20	24.2	0.6	13	27.3	1.6	11
- " -	146	27.3	1.0	18	23.8	0.6	14	27.3	2.1	12
- " -	196	27.2	0.2	19	25.0	1.7	11	26.7	1.7	13
S. viminalis	013	31.3	0.3	12	23.7	0.9	16	26.4	1.7	14
- " -	101	32.1	1.0	9	22.7	1.5	20	25.7	3.5	15
- " -	021	34.6	11.0	5	26.5	3.2	7	25.6	1.7	16
- " -	115	32.2	0.5	8	22.8	1.6	18	25.5	1.2	17
- " -	102	39.2	0.3	1	22.7	1.3	19	25.2	1.2	18
- " -	198	34.8	1.2	3	32.9	2.4	2	25.1	1.7	19
S. caprea x S. viminalis	040	31.6	0.4	10	26.5	0.7	8	24.9	1.6	20

Table 10: Average Mineral Contents for Willow Bark and Wood (after Choong et al., 1983).

Species & Tissue	Observation	Mineral Contents							
		Ash	N	K	Ca	Mg	Mn	Zn	P
		%			(ppm)				
WILLOW									
Outer-bark	10	11.5	371.8	2,905.0	40,210.0	1,014.0	359.8	177.6	241.5
		(19.2)[a]	(35.6)	(47.0)	(22.0)	(26.0)	(36.0)	(31.5)	(79.1)
Inner-bark	10	13.1	497.7	7,671.0	44,800.0	718.5	291.0	164.7	590.0
		(8.0)	(36.7)	(25.0)	(16.5)	(42.6)	(56.0)	(16.1)	(22.3)
Sapwood	10	0.9	204.8	2,185.0	1,106.5	119.4	94.1	36.8	441.2
		(22.2)	(48.8)	(19.0)	(10.1)	(40.0)	(12.5)	(30.3)	(33.8)

[a] Values in parentheses are Coefficients of Variation (%)

The level of production is influenced by the choice of species and number of stools per hectare (Table 11) as well as by the soil fertility, pH and climatic conditions. The length of the harvesting cycle exerts a strong influence upon biomass production (Table 12) as well as the age of the plantation (Table 13). Obviously, management has a large influence upon the magnitude of growth and clone, spacing, harvesting cycle, and stand-age interactions.

Table 11: Production of One-year Coppice Growth on Two-year-old Roots (data from Hathaway and van Kraayenoord, 1981).

Clone	SPACING (m)				
	0.3x0.3	0.3x0.6	0.3x1.2	0.6x1.2	1.2x1.2
	Tonnes/ha green wt				
S. daphnoides 'G'	28.1	24.8	18.7	15.3	7.9
S. purpurea 'Booth'	35.6	41.9	31.5	24.8	18.6
S. purpurea 'Irette'	43.9	41.6	47.1	37.2	26.4
S. viminalis 'Gigantea'	35.9	43.4	46.0	43.0	37.5
S. matsudana x alba 'nz1002'	37.8	37.5	46.7	46.1	41.0
S. matsudana x alba 'nz1046'	38.6	42.0	54.9	47.6	42.2

Table 12: Annual Biomass Production from One- and Two-year Harvesting Cycles (data from Hathaway and van Kraayenoord, 1981).

Clone	Harvest	
	Annual	Biennial
	Tonnes/ha/yr green wt	
S. purpurea 'Irette'	58.7	39.0
S. matsudana x *alba* 'nz1002'	56.4	62.4 (0.3 x 0.6 m)

(Spacing 0.3 x 1.2 m)

Table 13: Annual Biomass Production (m^3 ha^{-1}) from Natural Willow Stands (data from Levickij, 1967).

S. viminalis								
Age	1	2	3	4	5	6	7	8
Volume	8.0	8.3	11.0	13.5	16.0	13.4	11.2	9.4
S. triandra								
Age	1	2	3	4	5	6	7	8
Volume	9.0	9.5	11.6	14.5	13.0	10.5	8.1	6.1

The mineral content in plant tissues is partly affected by the production level of the crop. It has been shown for young willow plants that the nitrogen concentration of the different plant parts increases linearly with increased nitrogen supply (Ericsson, 1981 a, b). Thus, harvesting a high-yielding willow plantation removes more nutrients in absolute (per hectare) as well as in relative terms (per tonne of harvested biomass) compared with one that is low-yielding.

Both spacing and rotation length affect the quantity of nutrients removed in harvested biomass. Decreased plant density, as well as increased rotation length, reduce the proportion of high nutrient-containing branches and bark in the harvested biomass and, thus, reduce the removal of nutrients from the forest site.

Harvesting the total above-ground biomass substantially increases losses of nutrients from the site. By harvesting the stems after leaf fall, some 40% of the nitrogen used for shoot growth will be left on the forest floor.

The removal of nutrients can be reduced still further by harvesting the stems and branches at the time of growth cessation but prior to leaf abscission. At this stage of stand development, stem nutrients (Grigal *et al.*, 1976) and water contents (Nilsson, 1982) are at their lowest levels. Of course, a procedure must be developed to leave leaf litter well distributed over the site.

FERTILIZER APPLICATION AND IRRIGATION

Data in the literature suggests that the growth potential of willows is large but that nutrient requirements of intensively-managed willow plantations are high since biomass formation is closely linked to nutrient uptake in plants.

Where the land available for short-rotation forestry is limited, high production levels per unit area will most probably be a prerequisite if this domestic energy source is to achieve importance. High yields from willow can be achieved, as seen from the literature, without large inputs of nutrients and water, provided plantations are confined to first-class soils. However, large-scale production of willows for conversion to energy will probably be restricted to less productive sites, sites often characterized by adverse climatic and pH conditions. The fertility of these marginal lands is often poor.

Water may also act as a growth-limiting factor in these areas, either by a low water-holding capacity of the soil or because of inadequate precipitation during the period of active growth. Although soil water content may be adequate, other factors, such as low pH on peat lands, may prevent necessary root growth for its utilization.

The need for an adequate water supply in a willow plantation is particularly important because the water-use efficiency of Salix is less than for other broadleaved tree species. The water consumption of Salix alba per m^2 leaf area was 60% to 80% higher than for two poplar clones and the biomass production per unit of water consumed was two-thirds that of Alnus glutinosa (von Braun, 1974; 1976). The evapotranspiration in young willow stands located in southern Sweden on hot, clear days can be as high as 5 mm day^{-1} according to Grip and Perttu (1982).

In order to obtain a sufficient production level on the less productive lands, fertilization and irrigation or drainage practices may be required.

The present state of knowledge concerning the possible gain from a fertilizer-irrigation system is limited, yet this knowledge is necessary in order to economically evaluate the feasibility of production-stimulating activities.

One attempt to maximize the stem biomass production in a willow stand located on a sphagnum mire has recently been reported by Elowson (1981). The ecosystem was gradually saturated with nutrients; the rate of supply was adjusted to match the rate of uptake. Thus, the supply of nutrients was increased in parallel with accumulating biomass. Once the ecosystem is saturated with mineral nutrients, it is assumed that fertilizer application will only be required at a relatively low level to compensate for nutrient immobilization or losses in harvest. The major part of the nutrients needed for tree growth will come from litter decomposition at this stage and from nutrient cycling within the trees. This experiment is still in its initial stage. However, experiences gathered from a similar experiment started in 1974 on sand with Scots pine are supportive (Aronsson and Elowson, 1980). The results show that very high levels can be achieved on otherwise unproductive lands by the proper use of a fertilization-irrigation system. The water-holding capacity of the soil was improved and a high level of fertilizer utilization was achieved.

A high level of fertilizer utilization is desirable not only for economic reasons but also from an environmental point of view. Nutrient losses to streamwater and groundwater will detrimentally increase natural eutrofication.

A large single dose of nutrients temporarily increases the soil nutrient concentration to high levels, levels actually harmful to willow roots (Ericsson, 1979).

The key to maintaining nutrition and growth in cultured ecosystems is, according to Ingestad et al. (1981), the nutrient flux density (amount of nutrients available per unit of time and unit of area) rather than the concentration. Fertilizer should, therefore, be applied to increase the natural flux of nutrients but not the nutrient concentration of the soil. The applied fertilizers must be in concentrations not greatly different from the current mineralization rate in order to be efficiently utilized by plants and associated soil microbes. Such fertilization requires many small supplies during the growing season, all of which should be adjusted to the current uptake capacity.

Conclusion

Energy plantations of willow to be grown on infertile soils have a high nutrient requirement for fertilizer applications during stand establishment. Once the plant-soil-microbe system is saturated with nutrients, fertilizer additions will only be required to compensate for the nutrient losses due to harvesting and microbial immobilization. The nutrient losses due to leakage will probably be small because of the perennial character of the root system (Korsmo, 1982).

FINAL CONCLUSIONS

More information is needed in the following areas to fully understand the nutrient cycles in willow plantations and the impact of different management practices on these processes:

- the quantitative nutrient uptake in stems, leaves and roots in relation to species, production level, spacing and stand age
- the effect of management on root growth, production, nutrient consumption and turnover
- litter production and mineralization in relation to species, spacing and stand age
- the long-term effect of rotation length, species, spacing, and number of harvest cycles on site productivity
- the possible gain in stem biomass production achievable by the use of a fertilization-irrigation system
- methods of stimulating the natural processes of nutrient cycling
- additional information on clone/site/climate influences on the nutrient cycle

* * * * *

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POOR

QUALITY

ORIGINAL